Analysing data from the SuperFGD prototype test with a beam of neutrons

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Abstract
The Super-Fine-Grained Detector (SuperFGD) has been selected as the main neutrino target for an upgrade of the ND280 detector in the T2K experiment. A SuperFGD prototype was tested with a beam of protons at CERN in 2018 and with a beam of neutrons at the Los Alamos National Laboratory in 2019. The tests of the response of the detector to neutrons are of great interest in measuring anti-neutrino interactions. This study aims to analyze data from the neutron beam tests. An event categorisation is performed as a first step to identify the various particle types issued from the main neutron interactions.

1 Introduction

The T2K (Tokai-to-Kamioka) is a long-baseline neutrino oscillation experiment in Japan that sends a beam of muon (anti-)neutrinos, generated at the J-PARC accelerator in Tokai, to the Super-Kamiokande far detector at Kamioka at a distance of 295 km. The T2K experiment consists of a set of neutrino detectors [1]. The Interactive Neutrino GRID (INGRID) near detector monitors the beam stability. In order to study neutrino oscillations in a narrow range of neutrino energies the ND280 near detector, 280 m away from the target, and Super-Kamiokande, 295 km away, are both placed 2.5 degrees off of the beam axis. The ND280 measures the flux, energy spectrum, and flavor content of the neutrino beam before any oscillations occur. The ND280 consists of a Pi-Zero detector (POD), an electromagnetic calorimeter (ECal), three Time Projection Chambers (TPCs), two Fine-Grained Detectors (FGDs), and a side muon range detector (SMRD). All enclosed within the UA1 magnet [2]. The configuration of the ND280 can be seen in Figure 1. Super - Kamiokande is a water Charenkov detector that measures neutrino oscillations.

The T2K collaboration has submitted a proposal to extend the running of the T2K and enlarge the physics potential of the experiment to reach 3 σ sensitivity on CP violation. The experiment will benefit from a more intense beam and an upgrade of the ND280 detector is required, aiming to reduce the systematic error from 6% to 3% [3]. The improvements considered are to increase the acceptance of particles propagating backward or perpendicular to the neutrino beam and to lower the detector threshold.

The selected design for the ND280 upgrade is the Super-Fine-Grained-Detector (SuperFGD), two High Angle TPC (HA-TPC), and six ToF planes. The upgraded configuration is shown in Figure 2. This report concentrates on the SuperFGD.

1.1 The SuperFGD and its prototype

The Super Fine-Grained Detector is the target for neutrino interactions in the ND280 near detector at the T2K experiment. It has dimensions of $192 \times 192 \times 56$ cm^3 and a total mass of about 2 tons. The Super FGD is a scintillator that consists of ≈ 2 million optically independent cubes of dimensions $1 \times 1 \times 1$ cm^3. Wavelength-shifting fibers go through each cube in the X, Y ,and Z directions. When an interaction occurs in the scintillating cubes, the target material reacts emitting light which is absorbed by a Wavelength-shifting fiber and re-emitted isotropically with a different wavelength inside the fiber. A fraction of this light undergoes a total internal reflection and goes along the fiber to the Multi-Pixel

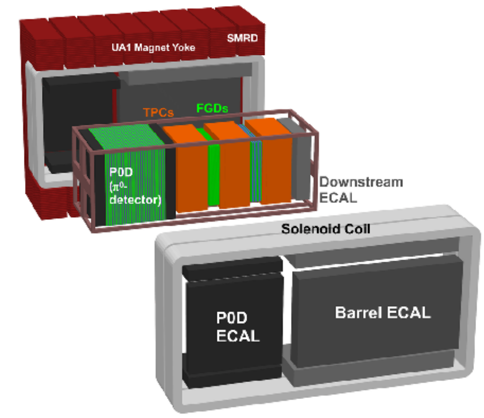


Figure 1: Exploded view of the current ND280 off-axis detector.The neutrino beam enters the detector from the left [1].

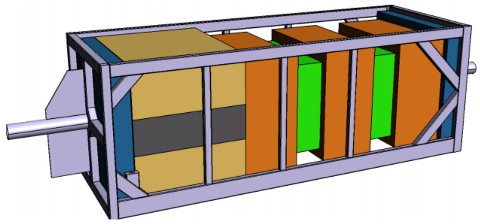


Figure 2: 3D Model of the ND280 upgrade detector. The neutrino beam enters the detector from the left. The two High-Angle TPCs (brown) and the SuperFGD (gray) in the middle will be installed. The tracker system composed by three TPCs (orange) and the two FGDs (green) will remain unchanged [4].

Photon Counter (MPPC). At the MPPC the photons are converted to electrons through the photoelectric effect and later signal amplification. Finally, the signal is transferred to the readout electronics, where it is processed and digitized.

The detector design of the Super FGD will allow 4π angular acceptance for neutrino interactions at the near detector and will provide lower energy thresholds, and excellent timing [5].

Two SuperFGD prototypes have been constructed and tested. One is a small $5 \times 5 \times 5\,\text{cm}^3$ detector and the second one is a $24 \times 8 \times 48\,\text{cm}^3$ detector consisting of 9216 cubes. This study is done using the second prototype. The SuperFGD prototype was tested in the T9 beam environment at CERN with a beam of hadrons and electrons in 2018 and at the Los Alamos National Laboratory with a beam of neutrons in 2019. This project uses data from the neutron beam tests. To measure anti-neutrino interactions in the detector ($\bar{\nu} + p \rightarrow l^+ + n$) the study of the detector response to neutrons is of deep interest.

1.1.1 LANL Neutron beam

At the LANL a proton beam of 800 MeV strikes a tungsten neutron production target and neutrons, gamma rays, and charged particles are produced. The charged particles are removed from the beam by permanent magnets. The neutrons and gamma rays travel the distance of flight of 90m and arrive at the detector. The gamma rays arrive first because they travel at the speed of light. The neutron beam has energies ranging between 0.1 to 600 MeV, so it becomes broader as it travels the flight path with the higher energy neutrons arriving before the lower energy neutrons.

2 Analysis

2.1 Data structure

When a signal occurs in the detector a 2D hit in one view (XY, XZ or YZ) is produced by the information delivered by the MPPC. Voxels are created by matching hits from 3 different views from the same cube to produce a 3D object. The voxels created can be both track(signal) voxels or crosstalk voxels. The scintillator cubes in the Super FGD are not completely optically independent. The light in one cube may leak to other cubes and be picked up as a signal by the MPPC. These cubes are called crosstalk cubes and the voxels, reconstructed from them - crosstalk voxels. The cubes where a real interaction occurs are called track cubes, from them we get reconstructed track voxels. Crosstalk hits have less energy, lower amplitude, and occur at later times compared to the main hits from real interactions. To separate the two types, we define voxels with energy in one view > 50 p.e. as track voxels. A group of voxels, close together in space and time, forms a cluster. All hits in a particular time window give a single event.

2.2 Kinetic energy of neutrons and deposited energy in the detector

The time of a hit is the time of the signal with respect to the time of the trigger given in units of 2.5 ns. The time of flight of the neutron is calculated using the time of the first hit of an event. ToF of a neutron is the sum of the time of the hit in units of second, the offset coming from the delay of the trigger signal and the time the photon takes to travel the 90 m distance between the beam source and the detector (90/c). This ToF be used to calculate the velocity $v = 90/\text{ToF}$, and the kinetic energy of the neutron using the relativistic kinetic energy equation,

$$KE = (\gamma - 1)mc^2 = \left[\frac{1}{\sqrt{1 - \frac{L^2}{t^2c^2}}} - 1 \right] mc^2. \tag{1}$$

Where t is the time of flight of the neutron that is given in units of 2.5 ns. and is converted to second, c is the speed of light, L is the flight distance of the neutrons = 90 m., v is the speed of the neutrons, $m = 939.565$ MeV - the mass of the neutron. For simplicity we work in natural units, hence, c = 1 and the Kinetic energy is calculated in MeV.

Figure 3 shows the energy spectrum of the neutrons, calculated using the time of flight. This is compared to Figure4, the expected energy spectrum of neutrons determined by LANL. The two plots are in agreement.

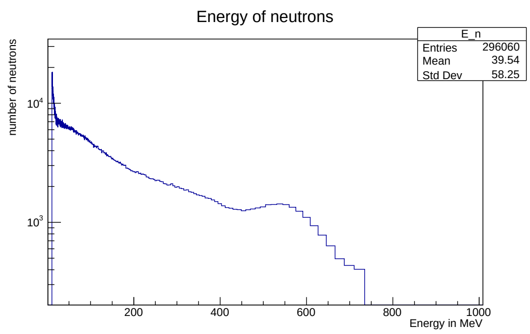


Figure 3: Energy spectrum of the neutron beam, calculated using ToF

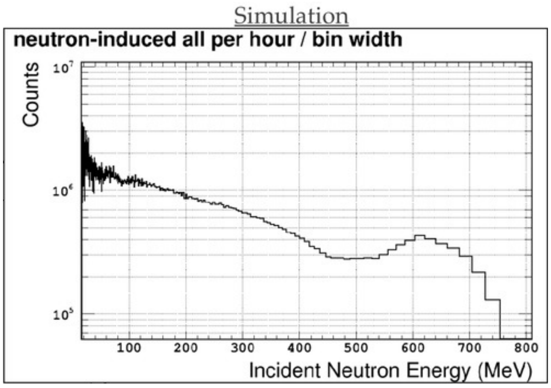


Figure 4: Measured and simulated energy spectrum of the neutron beam from LANL using the SuperFGD prototype [6].

The energy deposited in the detector can be calculated by summing the energy of all hits in each event. This is given in photoelectrons (p.e.) and is referred to as the hit charge. Figure 5 shows the sum of the energy of the clusters in the events vs. the Kinetic energy of the neutrons. The plot gives a correlation between the energy the detector sees and the energy we expect the incoming neutron to have. In the plot, a structure is observed for KE of the neutron between 300 and 700 MeV and for event charge $\approx$ 1500 p.e..To understand the origin of the structure the distribution of the number of voxels in the clusters in all events is compared to that in events in the region under study. The results are shown in Figure 6. Dedicated studies on the number of voxels per clusters for all events have shown that that region is characterised by a high number of voxels which might indicate track-like events.

2.3 Studies of the highest energy deposition voxels

The maximum energy voxels in each cluster are studied to understand the distribution of energy in voxels and clusters. Figure 7 shows the maximum energy voxel in each cluster divided by the total energy of the cluster (3 views). This shows the fraction of energy in the maximum energy voxels or the energy distribution in the cluster. The three views have peaks at 0.5 and 0.33. Figure 8 a) show the maximum energy voxel as a function of total energy deposition in the event, b) and c) show the maximum energy voxel divided by the charge of the cluster as a function of the number of voxels and the number of track voxels. The peaks at 1, 0.5, and 0.33 can also be seen in these plots. For events with a fraction ≈1 or 0.5, this means that almost all or half of the energy is concentrated in the maximum energy voxels. Hence, these events have 1 or 2 track voxels respectively suggesting that they are blob-like events with a yellow track voxel center and blue cross-talk voxels around it. On the other hand, the peaks around 0.33 and 0.25 correspond to events with 3 and 4 track voxels respectively. The energy of these events is more distributed through the cluster and is related to track like events. The observations made from Figures 5, 7 - 8 are the basis for attempting an event categorisation, and hence, event energy deposition categorisation, aiming to disentangle particle types.

2.4 Low energy deposition studies

Before defining the event categories we considered the possibility to reject electronic noise (noise clusters) by looking at the isolated deposition at low energy. To identify a soft cut the total charge per cluster is observed in all three views, in Figure 9 the YZ view can be seen. A cut was considered around the value of 70 p.e.. However, after examining some event displays of clusters with total charge below 70 p.e. - Figure 10, the following conclusions were made. First, it can be observed in Figure 10 and the other event displays that were studied, that the small cluster, which has charge < 70 p.e., appears in all three views. This implies that the cluster is not generated by electronic noise. Furthermore, the time delay between the two clusters is studied to assess the possibility that the low deposition cluster is associated to cross-talk. The time delay of the clusters is given by the time difference of the first hits in each cluster. This is found to be around 5 ns for most events. However, studies of the times of cross-talk hits and the main hits show that the expected delay between them is around 12 ns. Hence, the possibility of the low deposition cluster being cross-talk is rejected. Consequently, no soft cur was identified. Observing the time matching of the different views, XZ vs. YZ is shown in Figure 11, we conclude that the time matching is perfect and no cut is applied.

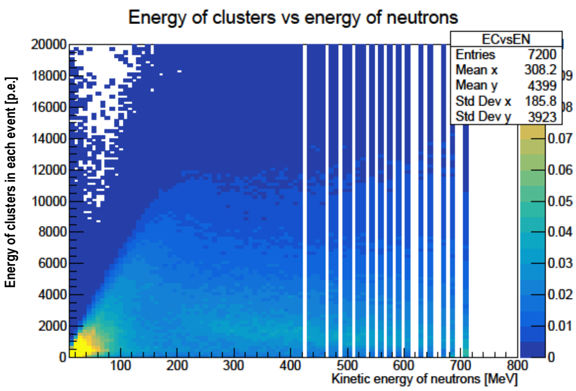


Figure 5: Sum of the energy of clusters in each event vs. the Kinetic energy of the neutrons, calculated from the time of flight of the neutrons. Both the energy of the hits and the Kinetic energy of the neutrons are calculated in the YZ view.

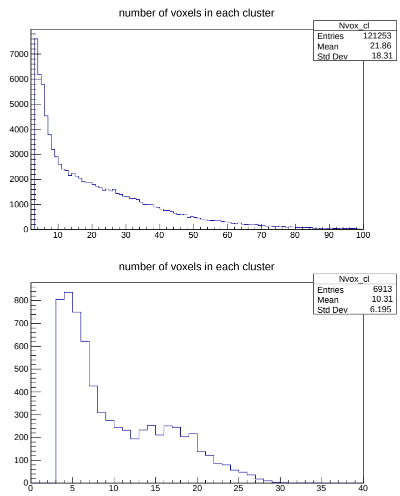
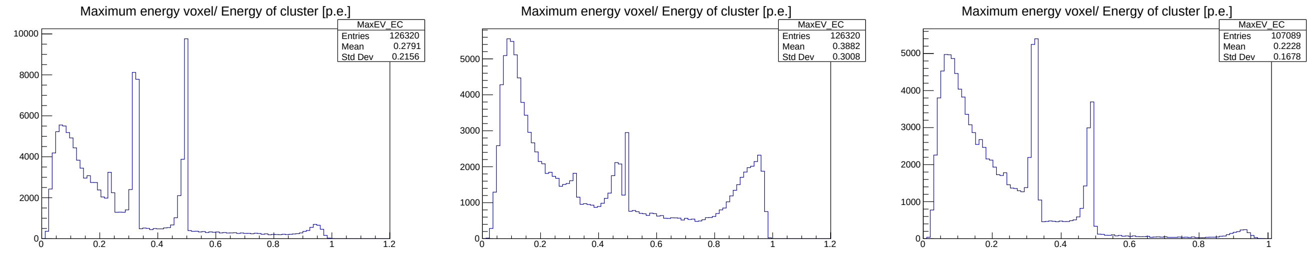
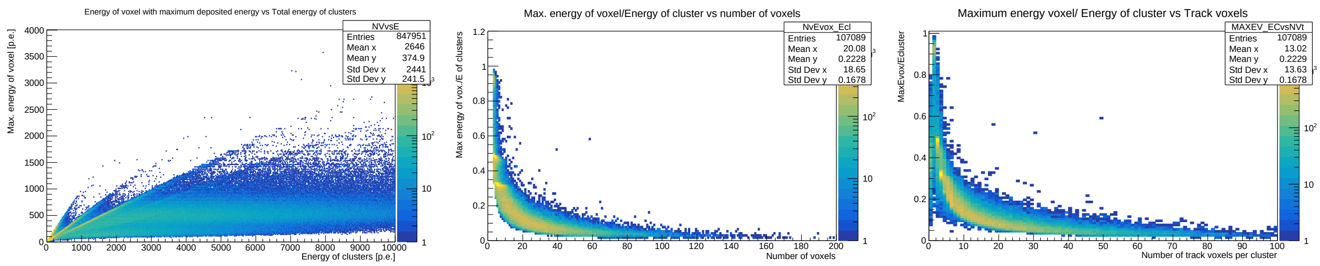


Figure 6: Number of voxels in each cluster top: in all events, bottom: in events in the region of interest.



(a) (b) (c)

Figure 7: Fraction of the total charge of the clusters deposited in the highest energy voxels in the a) XY, b) XZ, and c) YZ views.



(a) (b) (c)

Figure 8: a) Voxel with maximum energy deposition [p.e.] vs. charge of cluster [p.e.]. The lines have slopes 1, 0.5, 0.33 and 0.25. b) Fraction of the total charge of the clusters deposited in the highest energy voxels vs. number of voxels. c) Fraction of the total charge of the clusters deposited in the highest energy voxels vs. number of track voxels.

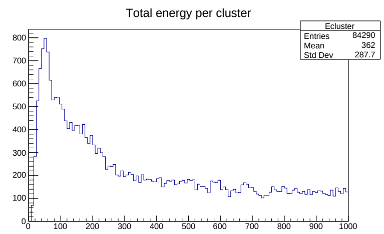


Figure 9: Total charge per cluster in the YZ view, in units of p.e..

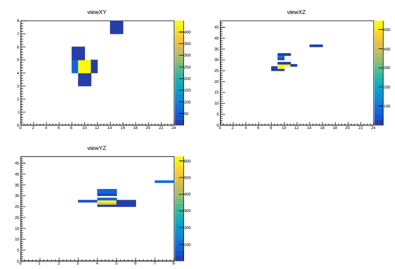


Figure 10: An event display of an event consisting of 2 clusters. The smaller cluster has charge < 70 p.e..

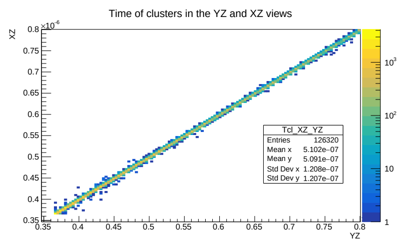


Figure 11: Time of clusters in the YZ vs. XZ view.

2.5 Event Categorisation

2.5.1 Linearity cut and number of voxels and track voxels

The linearity of a cluster is calculated using Principal component analysis. The linearity cut is defined at 0.9, with events with linearity > 0.9 passing the cut. Instead of calculating the linearity of the 3D cluster by constructing the 3x3 covariance matrix, it is calculated separately for the three views - XY, XZ, and YZ. To do this we consider three 2x2 covariance matrices, one for each view. This approach is taken because a significant fraction of the track-like events are found to pass the linearity in 2 views and fail in the third. This is observed when a neutron is going along the Z-axis, for example, in this case, the event will look linear in the XZ and YZ views, but it may look like a blob in the XY view.

The condition on the number of voxels is added because events with a small number of voxels pass the linearity condition even if they are blobs consisting of 2-3 voxels. The condition on the number of track voxels is added because track-like events should have at least 3 high energy voxels.

2.5.2 Categories

To classify the events we considered the following categories:

1. One blob events (1 cluster, fails the linearity cut in all 3 views or if it passes linearity cut, number of voxels < 4 or number of track voxels < 3)
2. Multi blob events (> 1 clusters + all pass the conditions for a blob cluster)
3. One track events (1 cluster, passes the linearity cut in at least 2 views, voxel number > 3, track voxel number > 2 in at least 2 views)
4. Track + other clusters events (> 1 clusters, at least one passes the track conditions)
5. Other (the events that don't belong to the previous categories)

Event displays from the 5 categories are shown in Appendix A. Applying these categories, the events were distributed as shown in Table 1.

Table 1: Distribution of events in each category

Event category	**Fraction of events**
1 Blob	52.1 %
Multi Blob	20.2 %
1 Track	15.9 %
Track and other clusters	7.9 %
Other	4.0 %

2.5.3 Studies of the Kinetic energy of neutrons and cluster charge using the event categorisation

The event categories as a function of the neutron Kinetic energy can be seen in Figure 12 a). The plot shows that low energy neutrons create more blob-like events while high energy neutrons create more track-like events. Furthermore, we can look at the deposited energy in the detector as a function of neutron Kinetic energy for each category separately in Figure 12 b) - f). Comparing this to Figure 5, we conclude that the structure discussed in Section 2.2 comes from track-like events, as expected. They correspond to Minimum Ionizing Particles where the total deposition per view is small. They suggest that the particle scapes the detector before fully depositing its Kinetic energy. Looking at event displays from the region around clusters charge = 6000 p.e and KE = 100 MeV the events are good candidates for stopping particles, such as protons, that lose energy fast and have short tracks. The events around clusters charge = 1000 p.e. and KE > 400 MeV can be identified as Minimum Ionizing Particles, such as muons and pions, that lose a low amount of energy per cm and have long tracks, many of which scape the detector before stopping.

3 Conclusion

The aim of this project was to analyse data from the SuperFGD prototype test at the Los Alamos National Laboratory with a beam of neutrons. The study of the detector response to neutrons is of great importance to measure the anti-neutrino interactions in the detector. The correlation between the expected kinetic energy of the neutrons and the observed deposited energy in the detector was studied. An attempt on event categorisation was performed aiming to disentangle particle types produced by neutron interactions

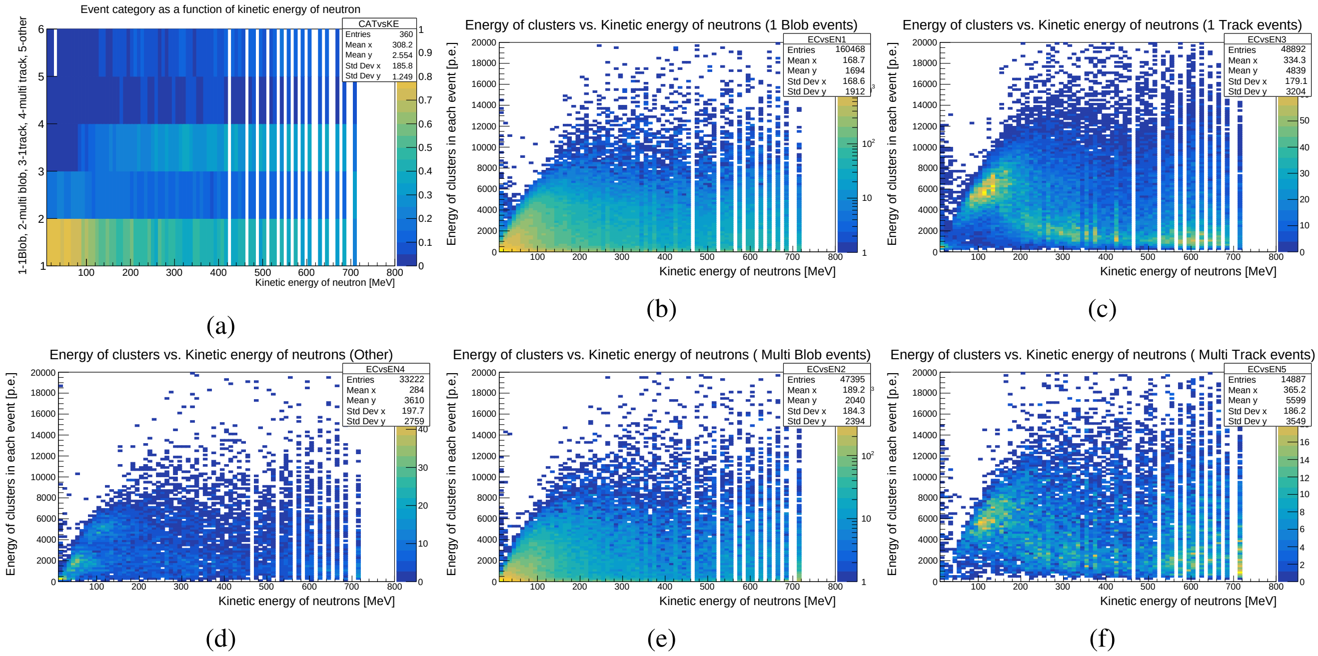


Figure 12: a) Event category vs. neutron Kinetic energy [MeV] b) - f) Total charge of clusters in an event vs. Kinetic energy of the neutron for 1 Blob events, 1 Track events, Other, Multi Blob events and Multi Track events respectively.

in the detector. Two regions were identified, where an increased energy deposition was observed - around clusters charge = 6000 p.e and KE = 100 MeV, and around clusters charge = 1000 p.e. and KE > 400 MeV, where the events can be identified as stopping particles and Minimum Ionization Particles respectively.

From the deposited energy in the detector, we can only reconstruct the Kinetic energy of the particles. In order to reconstruct the total energy, we need to identify the particles produced in the detector. Further studies of the different event categories and the particles associated with these events are crucial to reconstruct the total energy of an event and understand the energy deposition of different types of particles associated to neutron interactions in the detector. Since the neutrons are associated with anti-neutrino interactions in the detector it is important to understand the energy of the neutrons, so we can properly reconstruct the anti-neutrino energy.

Identifying the properties of neutron interactions in the detector, such as the types of events produced, the energy deposited, the difference between low and high energy neutrons is fundamental in improving the models that we use to interpret real data.

Analysing the energy deposited can help us assess the efficiency of the neutron momentum measured by the detector and help us understand if we see a bias and what the dependencies of the energy are. Moreover, studying different event categories may show that different events should be treated in a different manner.

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Appendix

A Event Displays of the 5 categories defined in Section 2.5.2

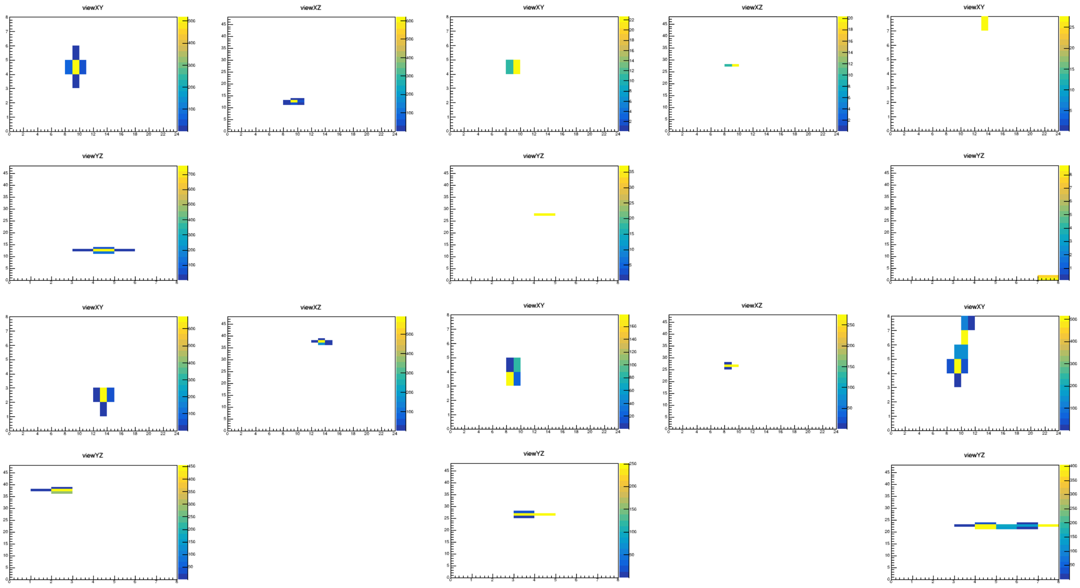

Figure A.1: 1 Blob events

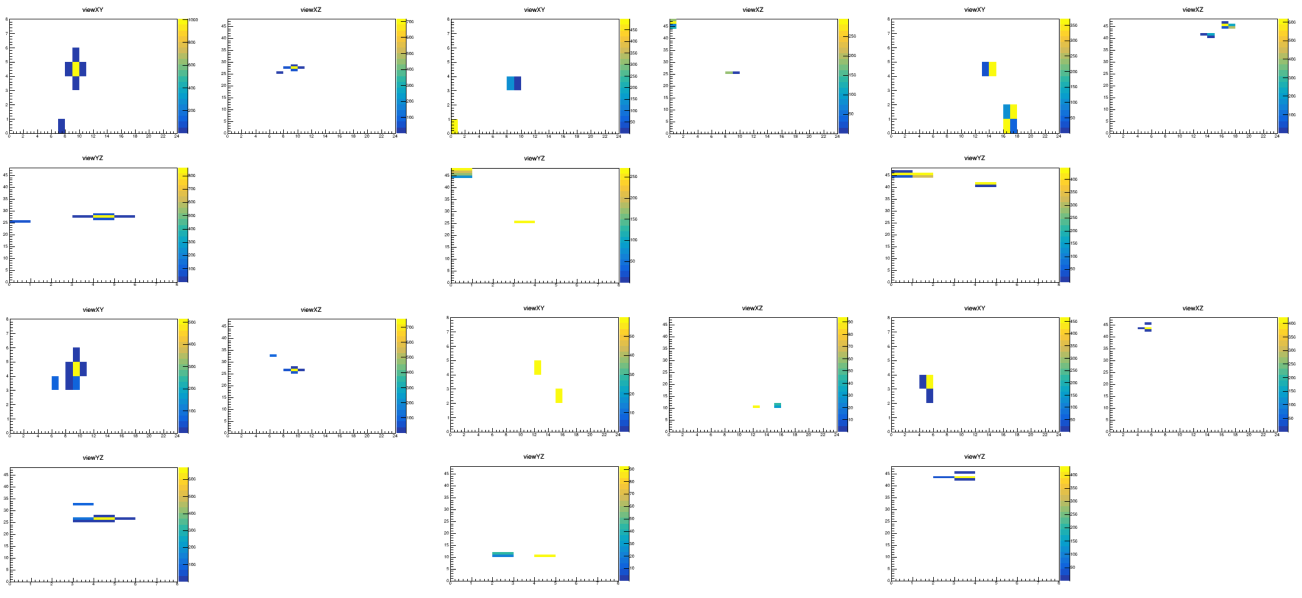

Figure A.2: Multi Blob events

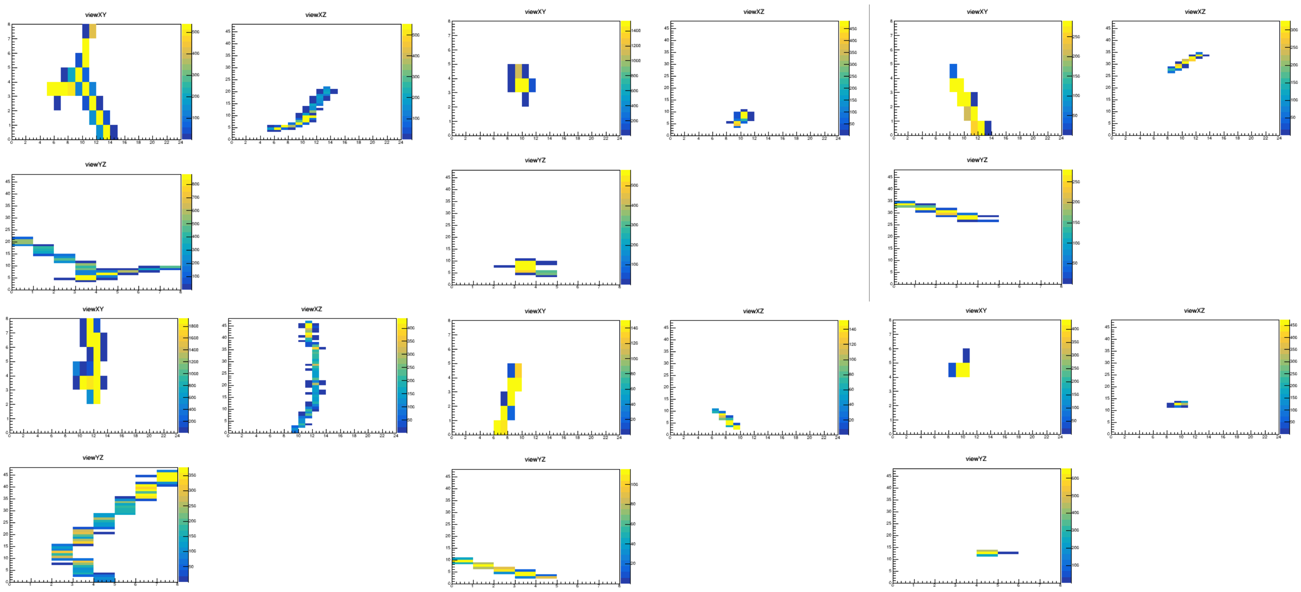

Figure A.3: 1 Track events

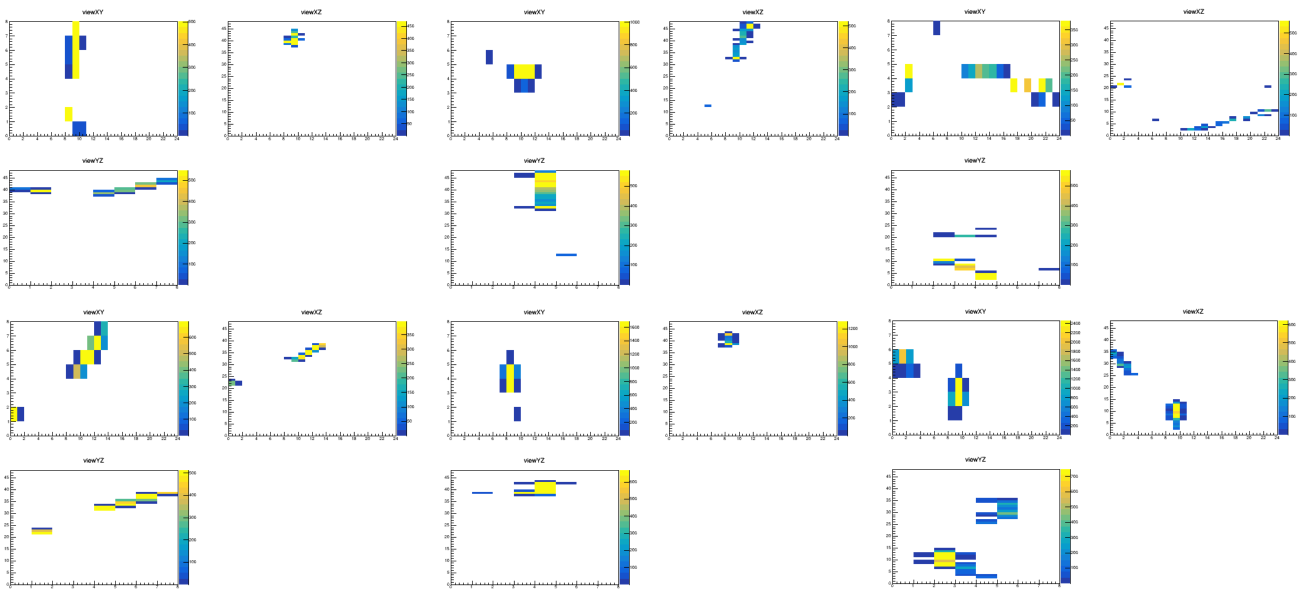

Figure A.4: Multi Track events

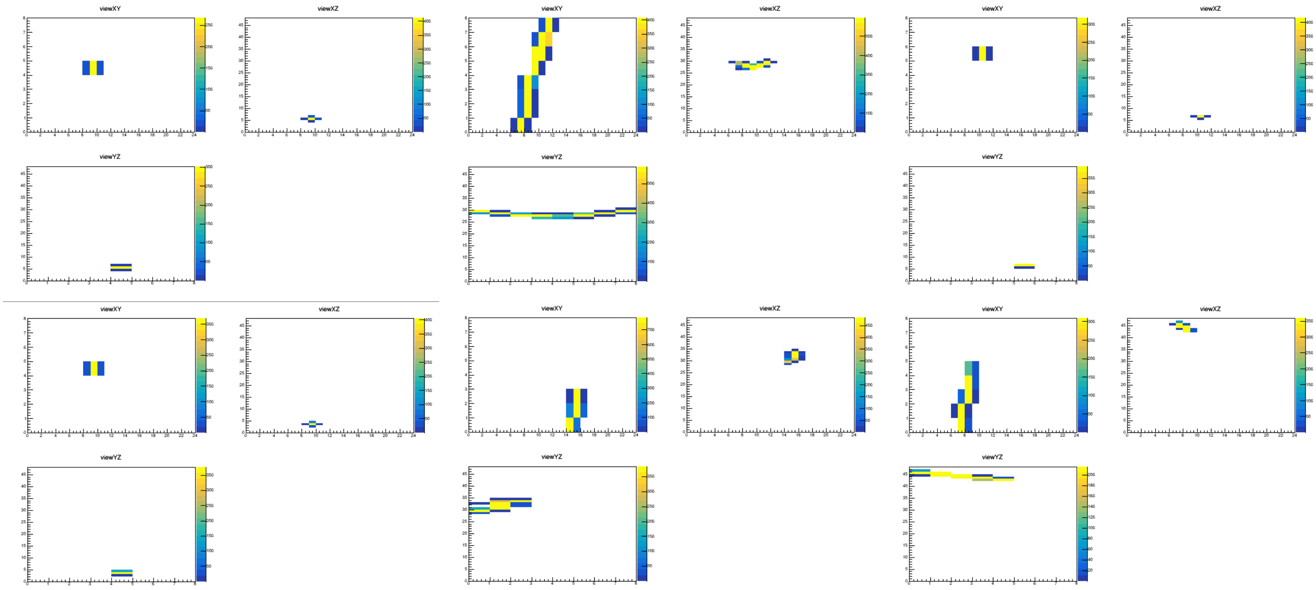

Figure A.5: Other events